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Mechatronic Design Process: A Survey of Product Data Model

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Abstract

The mechatronic system, as one of the most essential part of a modern product, plays a critical role when products become smarter and more complex. With the purpose of achieving an integrated design, the mechatronic system design process should be optimized.
The product data model is considered as an effective and efficient support to product development process. In fact, the objective of product data model is mostly to support Product Data Management (PDM) functions of Product Lifecycle Management (PLM) by providing a structure for product data creation, storage and exchange during the whole product lifecycle. Several product data models have been proposed for product design. However, few data models are dedicated to mechatronic system design.
This paper presents the different product data models, proposes specific criteria to evaluate them during the mechatronic system design process and points out the directions for the future research.

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Keywords: Mechatronic system design; integrated design; product data model

1. Introduction

The term Mechatronic originated at the Yaskawa Corporation from the combination of mechanics and electronics. With the development of technology, the meaning of Mechatronic has been broadened to include software and computation [1]. Nowadays, mechatronic systems are considered as the resulting integration of electrical/electronic systems, mechanical parts and information processing. Fig. 1 [2] presents these involved domains and the overlaps between them. Firstly, the actuator, represented in blue, is in charge of managing actuation forces and speed. It can be regarded as the combination of electronics and mechanics. Secondly, the embedded control, in green, is the overlap between the electronic domain and software domain. Thirdly, the sensors, in red, allow the system to response correctly to the different conditions. It is considered as the overlap between the mechanic and information domain. Finally, the communication, in yellow, is now considered as the central piece of the system, especially for distributed systems.

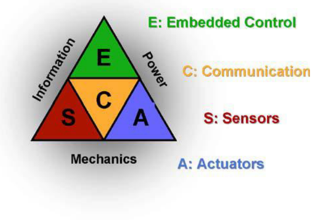

Fig. 1. Aspects of mechatronic [2]

The mechatronic system, as one of the most essential part of a modern product, plays a critical role when the products become smarter and more complex. Modern business strategies are aiming more and more at perfecting mechatronic systems [3]. Generally speaking, there are two tendencies toward engineering integration of mechatronic system, (1) physical integration [4] and (2) functional integration: (1) Physical integration focuses on spatial and weight

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optimization. Fig. 2 shows several levels of physical mechatronic integration. From the separated components to the merged components, the figure illustrates for the same system, how the components of the different domains can be integrated together. (2) Functional integration is not a simple superposition of different functionalities; it concentrates on providing a new functionality by integrating the existing ones.

Fig. 2. The different integration levels in mechatronic systems [5]

The concurrent mechatronic system design is complex and challenging. The first aspect of this complexity is related to the fact that the companies handle increasingly considerable amount of data and information from different domains, such as the design, production and maintenance [6]. The second aspect is that individual products are often born from different experts, which requires intensive collaboration between mechanical engineers, electronic/electrical engineers and software engineers [2]. The third aspect is that sometimes the engineers are located in different position of the world and they need to use powerful networking [7].

The product data model is used to filter, structure, integrate and control the voluminous information flow during the whole product lifecycle. Product data models were first introduced by [8, 9] in the 90's. They aim to structure product related information, facilitated their reuse or their exchange. Nowadays, different types of product data models have been proposed depending on the industrial context or the lifecycle stage. However, few data models are dedicated to mechatronic system design.

In this section, mechatronic system specificities have been presented. Due to these specificities, issues linked to mechatronic systems design have been proposed. The next section will introduce the product data models. In order to meet the highly requirement of integration during mechatronic system design process, specific criteria to evaluate the product data models are presented in Section 3. Finally, the authors draw the conclusion and point out the directions for the future research.

2. Review of Current Product Data Models

The main objective of product data model is to support Product Data Model (PDM) functions of Product Lifecycle Management (PLM) throughout the product life because product data model includes all the information that can be accessed, stored, served and reused by stakeholders throughout the entire product lifecycle [10,11]. Thus, a well-developed product data model can be used to support the mechatronic system design process.

Nowadays, several product data models and their extensions have been proposed. However, they cannot fully support mechatronic system design. Current data models will be revised in the following sections.

2.1. STEP (STandard for t e Exchange of Product)

STandard for the Exchange of Product model data (STEP) is actually a series of standards, known as ISO 10303 developed by experts worldwide [12]. STEP is intended to handle a wide range of product-related data covering the entire life-cycle of a product [13, 14].

As the area of application of the STEP standard is extremely broad, it is issued in numerous sections, identified as Parts. The Parts known as APs (Application Protocol) define the scope, context and information requirements of applications [15, 16]. STEP has developed more than forty standard APs for product data representation, and they reflect the consolidated expertise of major industries for more than twenty years, covering the principal product data management areas for the main industries [17]. In other words, the APs are specific data models based on STEP standard covering the entire lifecycle of a product or /and a certain industrial domain. Nowadays, the STEP APs are widely used in mechanical design domain. Some APs related to mechatronic system design are proposed. However, an AP which can systematically support the whole mechatronic system design process has not been fully developed.

AP 239 [18] provides an integration and exchange capability for product life cycle support data. It not only integrates the information for defining a complex product and its support solution, but represents the planning and scheduling of the tasks and the management of the subsequent work as well. Moreover, it provides a representation of existing or potential future products. Besides AP 239, other APs related to the different expert knowledge of mechatronic system have been proposed. AP 210 [19] describes the requirements for the design of electrical printed circuit assemblies (PCA). AP 214 [20] specifies the exchange of information between various applications which support the automotive mechanical design process. In this section, the STEP and its Application Protocols have been discussed. In the next section, the Core Product Model will be presented.

2.2. CPM (Core Product Model)

CPM (Core Product Model), an abstract model with generic semantics, initially developed at NIST (National Institute of Standards and Technology), can support the full range of PLM information [21].

CPM is based on two principles. First, the key object in the CPM is the artifact. Artifact represents a distinct entity in a product, whether that entity is a component, part, subassembly or assembly. Second, the artifact is an aggregation of three objects representing the artifacts three principal aspects: Function, Form and Behavior. CPM consists of two sets of classes, called object and relationship classes [22].

In order to meet the requirements of multidisciplinary design, some extensions of CPM have been proposed.

Zha et al [23] proposed the Extension of CPM Embedded System Model (ESM) which is a feature-based approach to the co-design of hardware (HW) and software (SW) in embedded systems. It allows the designer to develop a virtual embedded system prototype through assembling virtual components. The interfaces between HW/SW, HW/HW and SW/SW are proposed in this model. The interface feature largely expands the CPM model. To a certain extend it partially realized the collaboration between electronic and software domain.

The Product Family Evolution Model (PFEM) which extends CPM to the representation of the evolution of product families is developed by [24]. This model represents the independent evolution of products and components through families, series and versions. The information model representing product families is an extension of the CPM and consists of three sub-models: Product Family, Family Evolution, and Evolution Rationale.

The Mechatronic Device Model (MDM) proposed by [25] is an extension model of CPM. It supports the conceptual design of multiple interaction-state mechatronic devices, where the interactions between the use-environment and the device may have different qualitative structures.

In this section, CPM and its extensions have been discussed. As CPM is an abstract and generic product data model for new product development, some extensions of CPM have been proposed to solve certain types of problems during the mechatronic design process (ESM, PFEM and MDM). A product model based on the methodology KBE (Knowledge Based Engineering) named MOKA will be presented and discussed in the next section.

2.3. MOKA (Methodology and tools Oriented to Knowledge based engineering Applications)

The KBE (Knowledge Based Engineering) is proposed to manage the vast amount of data and its flow through complex systems during one product development process [26]. MOKA is a European research project with the aim to develop a methodology and tools to support the deployment of KBE application [27]. The Structure, Function, Behaviour, Technology and Representation are considered as five basic views for building the product model. The MOKA product model is shown on Fig. 3.

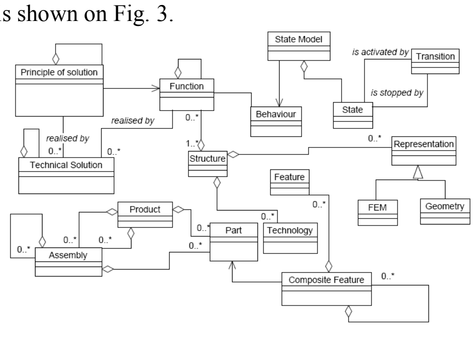

Fig. 3. MOKA Product Model

Different from the two product models introduced in the previous subsections, constraints which represent design restrictions are described within the MOKA product model. The constraint concerns the combinations of subsystems in a complex system. It implies the interface between two subsystems

Besides MOKA product model, MOKA also proposes the methodology of design process which defines how to resolve product choices subject to product constraints and the order in which design steps are executed and design decisions made [28]. MOKA describes design activities and rules in enough detail to enable them to be automated by UML Activity Diagrams.

Like MOKA, PPO model (Product-Process-Organization Model) which also focuses on the organizational process. The following section will present PPO model.

2.4. PPO Model (Product-Process-Organization Model)

Mechatronic system design process requires collaboration between different domains and engineers. The collaboration during design process becomes a problem that is exigent to be solved. Therefore, the process and organizational structure have been taken into account in the product data models.

IPPOP (Integration of Product, Process and Organization for engineering Performance Improvement) is a French RNTL network project labelled by the French Ministry of Economy, Finances and Industry [30]. The IPPOP project is based on the PPO model which describes information of product, process and organization. The product model developed during the IPPOP project is shown in Fig. 4. It consists of 4 main concepts: Component, Interface, Function and Behaviour.

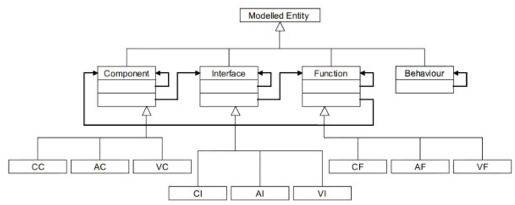

Fig. 4. Product model class diagram [31]

An interface class is described in the product model by which a component (mechanical, electrical and etc) may be linked to another. This interface class is classified into Common Interfaces (CI), Alternative Interfaces (AI) and View Interfaces (VI).

In the process model of PPO model, a particular activity is defined to describe collaborative actions in which the actors may collaborate in order to solve a conflict during the design process. Moreover, the PPO model develops the evolution of the design process in the design system because technical data is considered as versioned to take into account the temporal dynamics of the definition of the product [32].

As shown with recent PPO model developments, PPO is generally considered as an extensible data model [29]. Hence, a special extension for mechatronic system design can be developed based on PPO model.

Different data models have been chosen and discussed in the sections above. However, a product data model that can fully support mechatronic system design does not exist. The evaluation of the product data model will be presented in the next section.

3. Evaluation of different data models

Mechatronic system design requires a high degree of integration; therefore the complex mechatronic system is often divided into simpler subsystems or components and assigned to different design teams or engineers. The collaboration between different individuals and domains during the mechatronic system design process plays a key role to ensure that the results of their efforts are successful, especially to get an integrated system. Moreover, product evolution becomes increasingly significant nowadays in order to meet the rapid-changing market and short development lifecycle.

Considering the multi-disciplinary design, three criteria about interfaces are proposed in this paper: (1) macro level interface, which is a special link between components of different domains in the mechatronic system, (2) micro level interface, which provides an effective mean to support the detailed collaboration and (3) organizational interface, which guides all the design activities during the detailed design process.

As to the product evolution, we also propose two criteria about different types of evolutions. Fig. 5 presents the two types of evolution. The vertical arrow represents one product's temporal dynamic during the whole design process, which is called in this paper (4) vertical evolution. The horizontal arrow represents the evolutionary design of a product family in order to reduce development costs of new products, which is called (5) horizontal evolution.

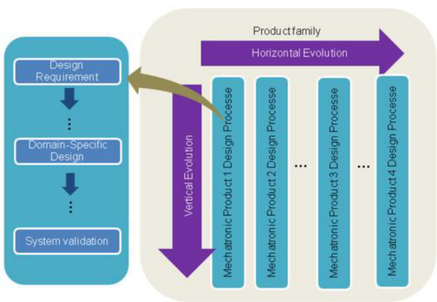

Fig. 5. Product Evolution

The data models that we have discussed above provide available approaches for mechatronic system design. Five criteria of collaboration have been chosen for evaluation: (1) macro level interface; (2) micro level interface; (3) organizational interface; (4) vertical evolution; (5) horizontal evolution. These criteria and the evaluation of the product data models will be discussed in detail in the section below.

3.1. Macro level interface

Macro level interface is the link between the components of different domains. A great number of components specialize to different domains and are under development by different engineers. With the purpose of two components to be interconnected, they must have compatible mechanical, electronic /electrical and software interfaces [34]. The communication between those components could be achieved through a direct interface between components or an indirect interface through a connector component [23]. These types of interfaces can help engineers to achieve a sound integration of the components. Therefore, a clear definition of this type of interface is quite significant because it decides to a great extend whether the mechatronic system can achieve an integrated design.

STEP standard only realized macro level interface in some specific domains. For example, AP 214 specifies the exchange of information between various applications which support the automotive mechanical design process; STEP AP 210 describes the information for the design of electrical printed circuit assemblies.

The Extension of CPM Embedded System Model defined the interface between hardware and software in embedded systems. However, the embedded system is not a real mechatronic system; sometimes it is just a part of mechatronic system.

Constraint has been represented in the MOKA product model which implies the interface between two subsystems.

In PPO model, an interface class is described by which a component (mechanical, electrical and etc.) may be linked to another, but it is very generic and should be further modeled for mechatronic system.

3.2. Micro level interface

The engineers need an interface which allows them to utilize information or data from other domains. It intends to help designers to collaborate or coordinate by sharing information through formal or informal interaction. Micro level interface provides an effective mean to solve this problem.

STEP Standard is a powerful tool which supports the exchange of geometric data between Computer Aided Design (CAD) systems, but it focuses on the electronic/electrical domain and mechanical domain. STEP does not provide an effective interface to fully support the data exchange in information processing domain.

A platform based on CPM Embedded System Model has been established which allows co-design by different engineers.

As to the PPO model, a prototype of software supporting the PPO model has been developed by the IPPOP project and an engineer can find all information necessary to achieve his task by using a specific Graphical User Interface (GUI) [32].

3.3. Organizational interface

The organizational interface is used to guide the design process. In the preliminary design phase, the engineers determine the principal solution according to the users' requirements, which will guide all the design activities during the detailed design phases. Thus, human communication and cooperation become additional factors which affect design integration. On one hand, the organizational interface transforms the users' requirements into the principal design solution; on the other hand, it informs the engineers how their part of the solution affects other parts.

STEP AP239 partially develops the organizational interface because it represents the planning and scheduling of the tasks, but it is still very generic for mechatronic system design because some specific characteristics of mechatronic system, such as data exchange in real time and conflict solving during the design process, have not been involved in this data model.

Organizational interface also partially exists in MOKA model. Although MOKA model provide an interface to describe the design activities and rules described by UML Activity Diagrams, it does not offer the design environment where engineers can take into account their own design situation and know how they can affect others.

An organizational interface has been developed in PPO model. On one hand, the organizational model in PPO points out the objectives to be reached from the view of the customer and company; on the other hand, it provides the parameters of design situation for all engineers in the design project. Moreover, a decisional framework has been developed in the organizational model. It defines different horizons for the decision making and manages the design process according to the engineers' needs.

3.4. Vertical evolution

Current mechatronic system design is a dynamic process. A static product data model is no longer suitable for current mechatronic system design. The product data model of mechatronic system should be an instantiation of a model evolving dynamically with the design process. Technical data is considered as versioned to take into account the temporal dynamics of the definition of the product. The product data model may be modified from time to time due to customers' requirements and market changes. The vertical evolution focuses on how to manage the products temporal data during one products development process.

STEP standard allows designers to exchange their design data and information at any time during the development process.

The MOKA model partially develops the vertical evolution because it describes the steps that realize a Product Model Instance from a Product Model.

The PPO model realizes the vertical evolution because technical data is considered as versioned to take into account the temporal dynamics of the product definition.

3.5. Horizontal evolution

Horizontal evolution focuses on how to manage the data of product families. A product family refers to a set of similar products that are derived from a common platform and yet possess specific features to meet particular customer requirements [33]. The development of new product in a family can be based on the successful design of its predecessors. This brings several benefits to the company and customers. Firstly, the product family development approach reduces development time and costs due to the development experiences of the predecessors. Secondly, the reliability of the new product can be dramatically increased thanks to the predecessors' successful design. Finally, extensive applications can be easily derived from the predecessors [24].

STEP AP 239 provides a representation of existing or potential future products, which allows the evolution of product families.

The Extension of CPM Product Family Evolution Model provides the representation of the evolution of product families.

The MOKA product model supports the horizontal evolution because it is one of approaches for Knowledge Based Engineering by which the experience, geometry and data that relate to a product family can be stored so that the time and cost of a product family development can be reduced.

However, the information related to a product family has not been explicitly proposed during the product design process to support the horizontal change of a mechatronic system in PPO model. The evaluation of different data models according to the criteria has been summarized in Table 1.

Table 1. Evaluation of the different data models

Product data model	Organisational interface	Macro level interface	Micro level interface	Vertical evolution	Horizontal evolution
STEP	Partial	Partial	Partial	Yes	Partial
CPM	No	Partial	Partial	Partial	Yes
MOKA	Partial	Partial	No	Partial	Yes
PPO	Yes	Partial	Yes	Yes	Partial

Table 1 shows the assessment of the studied product models according to the proposed criteria. With the purpose of organising design tasks more efficiently, the organisational interface has been included in STEP, MOKA and PPO. The product models, such as STEP, CPM and PPO, have partially developed the interfaces (macro level interface and micro level interface) to meet the requirements of collaboration between various experts and disciplines. All the product models discussed in this paper take partially product change into account.

4. Conclusion

The different product data models discussed in this paper show that much work for mechatronic system design has been realized up to now.

The first conclusion to be pointed out is that product data model is an effective support to the mechatronic system design process, for product data model can support all the product information throughout the entire product lifecycle. However, from the evaluation discussed in this paper, the current product data models cannot fully support mechatronic design. As a result, the second conclusion is that the current product data models should be further developed in the future.

Our future work should be divided into two parts. Firstly, the interface in the product data model of mechatronic system should be further improved to meet the requirements of collaboration.

Another issue should be focused on in the future research is perfecting the product evolution in the product data model in order to shorten the development lifecycle and reduce the development cost.

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